John August Roebling – The Niagara Railway Suspension Bridge

Göran Werner

THE BACKGROUND 1845-1848

At the beginning of the 1840s railways had become the transport of the future. As a comfortable means of travel, they allowed the travel industry to grow rapidly in many places. In 1845, for example, 50,000 visitors were recorded going to Niagara Falls, amounting to a doubling of tourists in five years (Berton 1992). The two big railway lines, Canada's Great Western and the New York Rochester and Niagara (called the New York Central today), recognised the potential and both planned independent routes to the famous waterfalls. The civil engineer Charles B. Stuart identified a way of doubling the profits of both companies by having both lines crossing the Niagara gorge on a single bridge. He had the world's most experienced bridge builder check the feasibility of a cable suspension bridge to carry both trains and road traffic. Only four engineers believed that building an approximately 245 metre (800 foot) bridge was practicable – Charles Ellet Jr., John August Roebling, Samuel Keefer and Edward W. Serrell (Berton 1992).

CHARLES ELLET'S PROPOSAL

Already in 1833 Charles Ellet Jr. wrote to his friend the engineer Charles B. Stuart that his highest aim was to create a suspension bridge across the Niagara gorge (Berton 1992). He did not know, he said, "in the whole circle of professional schemes, a single project which it would gratify me so much to conduct it to competition." This old friendship was certainly not a disadvantage when it came to the evaluation of the tenders for the construction of the bridge.

Because of this, Stuart turned to him with his initial enquiries in 1845, and Ellet presented his first proposals on 27 November 1845 (AL MS 6/ 41). In these he chose an optimal location for the bridge about 2.4 km down from the falls and suggested a bridge span of 229m and a height over the river of 64 m. The wooden bridge, hung on wire cables in turn ran over stone pillars, was to carry a 200 ton train safely and durably. When asked about the feasibility of the plan, he replied loftily to all doubts. As a justification he pointed to the suspension bridges that had already been built in Europe and to the fact that the necessary load-bearing capacity could be provided by the addition of main bearing cables.

The cross section consisted of a railway track in the centre, two lateral ways for common travel and two footways. It proposed ten main cables with a diameter of about 1.27 cm on each side of the bridge. Ellet calculated with the weight of the bridge itself of up to 700 tons, and a maximum load

of 400 tons, that the maximum tractive force on the main cables would be up to 2,300 tons. To avoid horizontal tension in the pillars, he proposed bedding the cables on the pillars as movable roller bearing. He estimated the cost of construction at $220,000, or $190,000 if the bridge were crossed a lower speed.

Awarding Contracts

After the question of the feasibility of the project had been thoroughly discussed, the Niagara Suspension Bridge Company put the construction of a combined rail and road bridge out to tender in the winter of 1846 (Edwards 1871), and was answered by offers by Ellet, Roebling, Keefer and Serrell. On 9 November 1847 Charles Ellet Jr. got the contract although Roebling's tender of $180,000 was $10,000 cheaper (Sayenga 1983). The decision of the Niagara Bridge Commission was possibly affected by the fact that Ellet had beaten Roebling and won a contract to build a suspension bridge in Wheeling only a few months ago and by the fact he was the first applicant. The contract contained the draft and the construction of a one-level bridge by 1 May 1849, with a thin width of 8.5 m between the sites, consisting of two 2.3 m wide lanes for horse and carriage, two foot ways, each of 1.2 m width, and a central railway line. The bridge was to have massive stone pillars and was to be able to support rail lines of up to 24 tons and a locomotive of up to 6 tons safely and durably.

The Temporary Bridge

Charles Ellet Jr. began work on the bridge at the start of 1848 and opened a temporary bridge with a gangway of 2.2 m already on 29 July. This bridge **(Fig.1)** was to allow the transport of construction materials and a limited amount of human traffic. It was also to be used as scaffolding for the construction of the bridge itself. The light wooden bridge roadway was hung on 14 wire cables of various diameters, which were to be used later as elements for the permanent bridge. The pillars were constructed as a wooden framework.

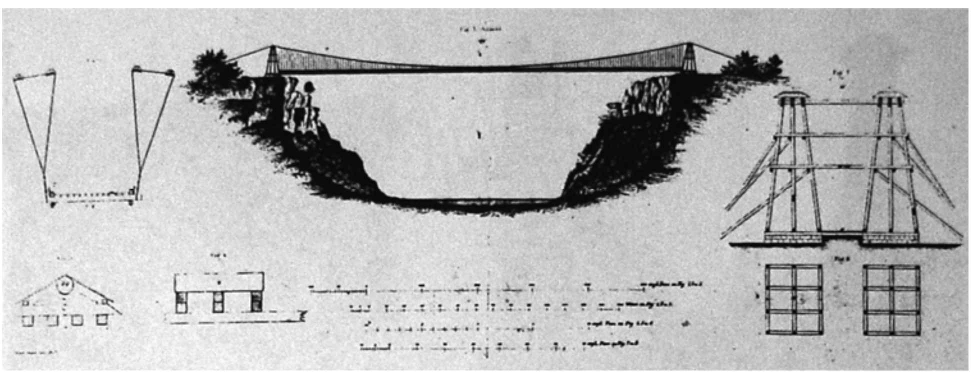


Figure 1. Niagara Bridge from Ellet, 1848 - 1854 (Werner 1973)

The planned permanent railway bridge was to hang on 16 cables each with 600 parallel wires wrapped in thin wire.

After the temporary bridge was opened, Ellet and the bridge company started to have financial disagreements, since Ellet was keeping the bridge toll. In the bridge company there were those who wanted to see the temporary bridge as a final solution, since the income raised from it was already considerable and the bridge was very popular (Edwards 1871).

THE PROPOSALS OF JOHN A. ROEBLING

A variant preliminary draft of Roebling's January 1847 proposal is worth mentioning **(Fig.2)**. It proposed a bending resistant construction similar to his previously completed canal aqueduct over the Delaware. The diagonal buttressing went over a dense set of joints. He was aware that the enormous burden of the railway combined with the necessary large span would definitely require an effective superstructure construction. The buttressing of the roadway construction was achieved with a dual diagonal casing in the same way as was built in his aqueducts. Roebling reduced the large span by the use of a traditional wooden supporting substructure near the bedding.

The practical experience he was able to gain building canal aqueducts was an important contribution to his significant recognition that simply making a suspension bridge heavier did not improve its bearing capacity and that this could be done more effectively by buttressing of the bearing structure. In all of his writings about the Niagara Bridge and later bridge projects too, he was very clear on the subject.

Roebling recognised that it was possible to optimise the girder's capacity by dispersing the horizontal bearing diagonal casing in pure support beams and thereby achieved a reduction in the weight of the bearing system. In his second and definitive draft of his 1847 tender he turned to wooden trusses **(Fig.3)**. He refers to the fact that in contrast to the usual lattice truss in which the diagonal beams lie over each other, his system interlaced the diagonal beams. This had the advantage of providing a higher rigidity than traditional flexible ties of the same weight. In Roebling's view the reduced effectiveness of the diagonals was acceptable because the bridge supports served to buttress the system. The main burden of the attack was taken by the cable suspension. (TR OZ D4 F7)

This final draft for the 1847 tender differs from Ellet's plans in several essential points. He was the first in the history of suspension bridges to introduce buttress supports in the form of a truss boxes into the system of a suspension bridge. As well as having advantages for the girders, which I will go into below, this construction allowed the rail and horse and carriage traffic to move separately on two different levels.

Roebling in this draft did not plan two lone standing pillars as cable bedding as Ellet had done, but rather planned a pillar portal on which rolling bearing cast iron saddles sat.

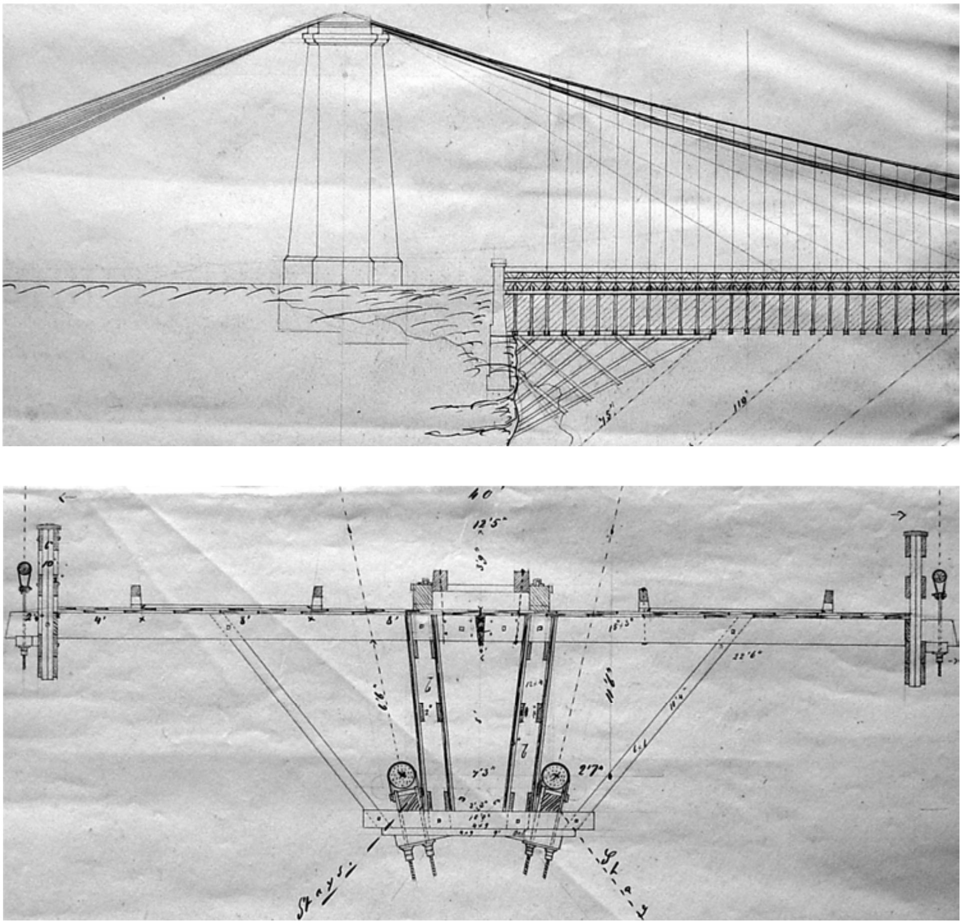


Figure 2. Roebling's 1847 preliminary draft for the Niagara Bridge (TR OZ D4 F8)

Roebling also introduced strands above and below the roadway to provide more system rigidity. The grouted anchoring of the cables in the cliffs was to follow Roebling's patented system as well as the patented way of manufacturing the cables by free spinning procedure.

In his specifications of October 1847 (TR OZ D4 F7) Roebling outlined the advantages of his double-decker solution over Ellet's one deck plan. Firstly he explained that it is not practicable to have horse and rail traffic so close to each other on one level of a bridge. The division between the two levels ensured that horses would not be directly exposed to the stress caused by the trains and also that no horses in closed boxes would fall from the bridge.

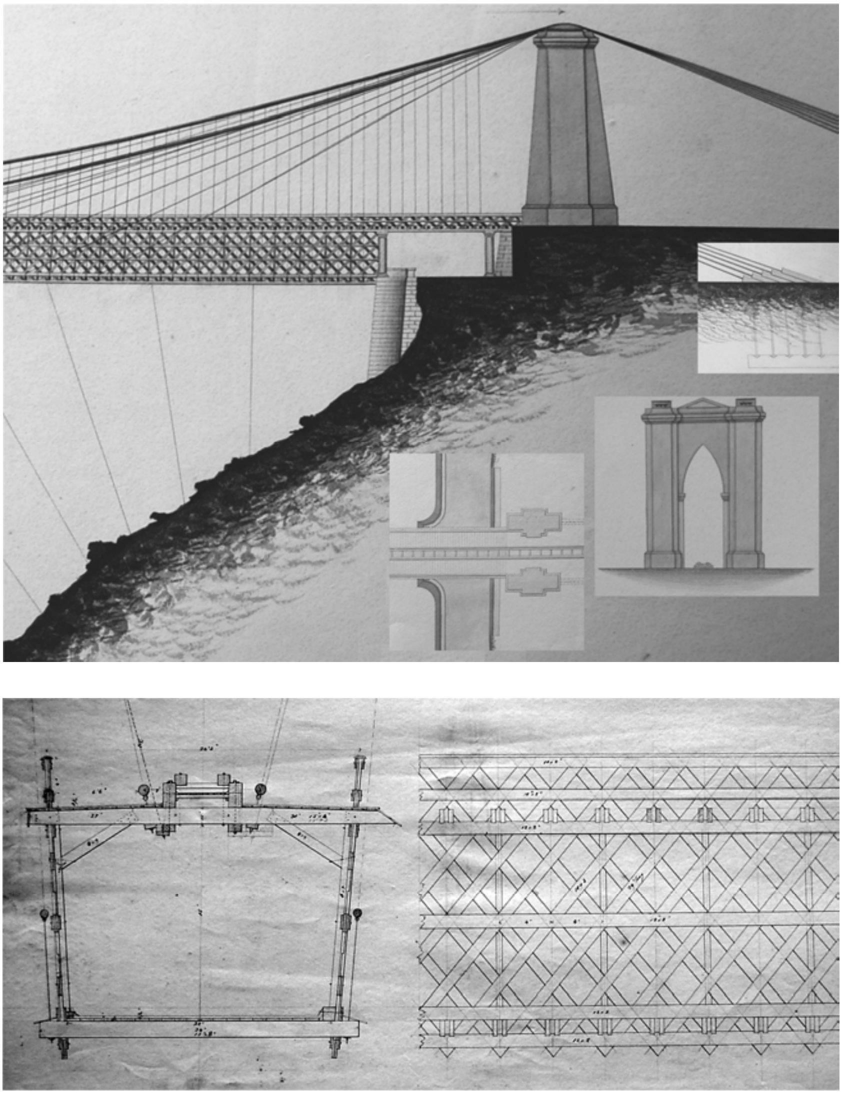


Figure 3. Roebling´s Niagara Railway Suspension Bridge Proposal, January - March 1847 (TR OZ D4 F7, F8)

The division into upper and lower decks proved to be particularly effective in improving the bearing capacity and durability of the whole bridge. Roebling recognised that a truss system is lighter than any comparable structure of the same rigidity and bearing capacity. In comparison to simple truss beams, a hung diagonal bridge box has the particular advantage that the danger of sideways movement was avoided by regular attachments. In Roebling’s view the grill boxes served only to spread the burden and stiffen the system. The main burden was carried by the suspenders, the stays and the wire cables. (TR OZ D4 F7)

Roebling gained this understanding from his theoretical knowledge of building wooden bridges and from his practical experience in producing ropes and canal aqueducts. Theoretical approaches beyond the known procedures of graphical statics and the suspension bridge design formulas of Navier cannot be shown in Roebling's draft and surveying work.

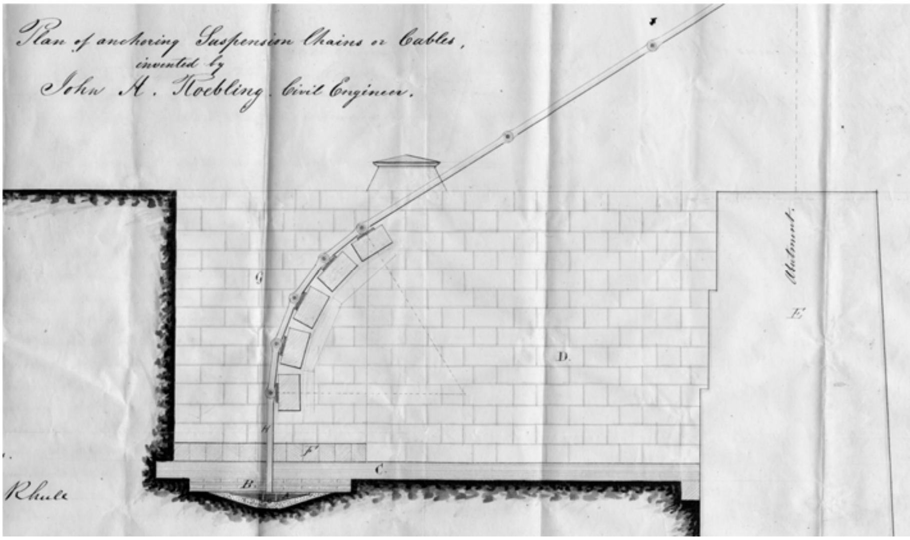


Figure 4. Patent: Improvement in anchoring suspension chains for bridges, 26.08.1846 (TR OZ D5 F30)

Compared to Ellet's draft, Roebling developed the supporting structure as massive pillar portal. It is possible that Roebling was led in this variant draft by considerations of the increased pressure of the horizontal wind and the expected vertical and horizontal stress from the railway, which should not be underestimated.

The cable grouted anchoring that Roebling had patented **(Fig.4)** foresaw fixing wrought iron eye-bars on an anchor plate deep in the ground of the development site and connecting it to the bearing cable from the foundations in a circular reverse fashion. The weight of the car lining over the anchor plate served the traction anchor of the bearing cable. His procedure differs from the Navier school that Ellet followed essentially by mortaring the whole anchoring in the development site so it would be airtight to avoid corrosion caused by contact with oxygen. Of course, subsequent maintenance or the replacement of individual chains was not possible.

The free spinning procedure that Roebling had already used in building his hanging canal aqueducts provided large scale and compact bearing cables. Ellet, for instance, in his 1846 Wheeling Bridge placed the cable as a parallel wire cable on the building site next to the bridge and when it was completed he pulled them over the supporting pillars. On the one hand Ellet was limited in cable cross section on weight grounds; on the other hand an equally distributed tension over the cable

section was not present. In unfavourable circumstances individual wires drooped in cable cross sections and other wires were tightened almost to breaking point.

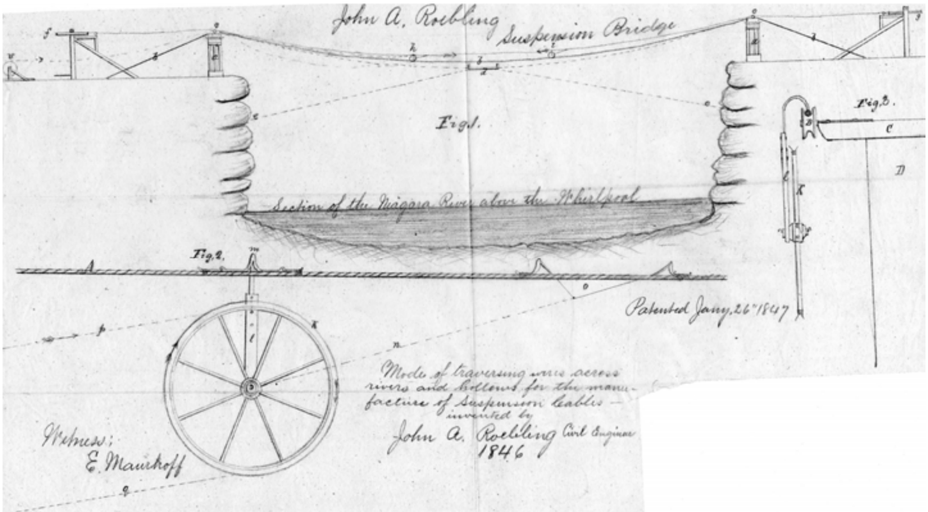


Figure 5. "Free spinning procedure" patent: Improvement in apparatus for passing suspension wires for bridges across rivers, 26.01.1847 (TR OZ D5 F30)

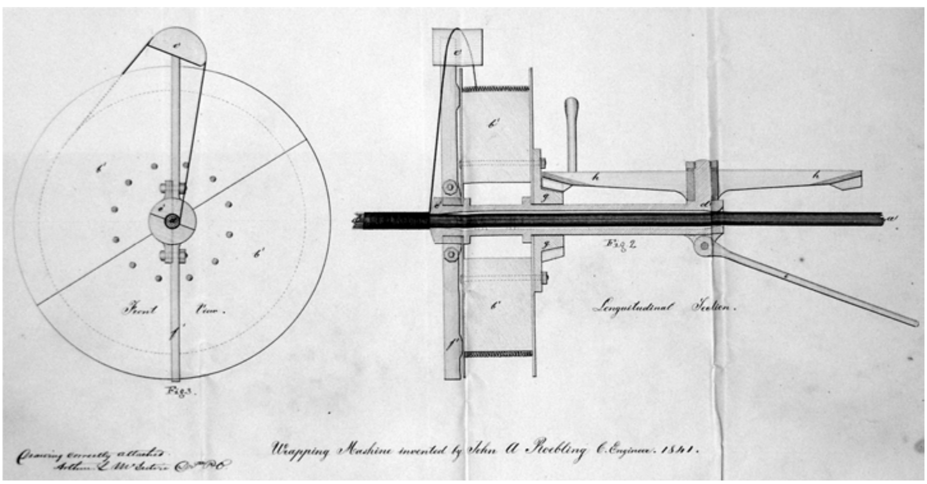


Figure 6. Patent: Improvement in the method of, and the machinery for manufacturing wire ropes, 16.07.1842 (TR OZ D5 F30)

Roebling in contrast brought the individual wires of the cables directly to where they were made by having an endless wire follow all along the length of the cable **(Fig.5)**. After the necessary number

of individual wires is reached the cable is pressed together with iron clamps and tied around with a red glued thin wire **(Fig.6)**. Along with the advantages outlined above, this method provided Roebling with maximum flexural rigidity, adding considerably to the rigidity of the construction.

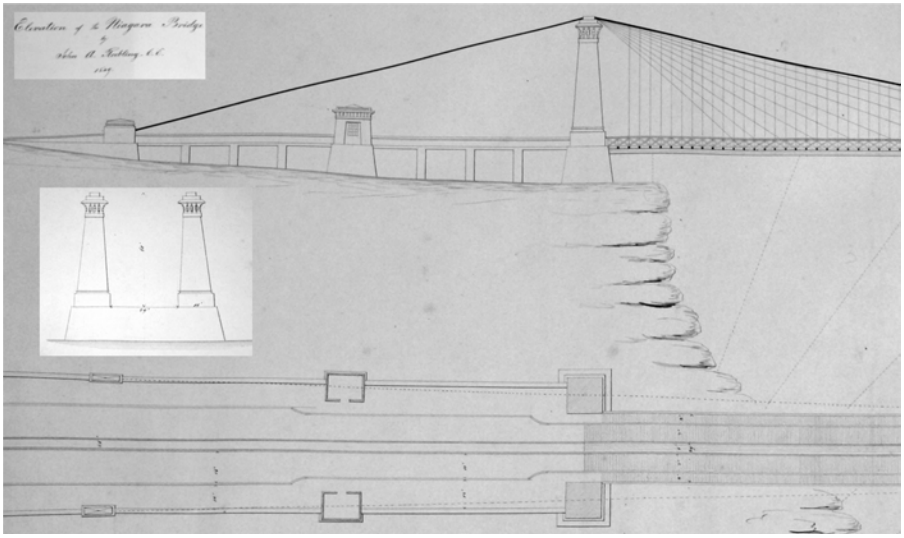


Figure 7. Roebling's suggestion for a one-deck bridge 1848/ 1849 (TR D4 F9)

Since Roebling had lost the contract to Ellet in November 1847, he first had to experience how his rival was on the verge of building the world's first railway suspension bridge. However, things were to develop in Roebling's favour. Charles Ellet took the income gained by charging people to cross the temporary bridge for himself. Since his clients thought this was unfair the contract parties became involved in legal wrangling, leading to the early ending of their work together. After the bridge building company split with Charles Ellet Jr. in the autumn of 1848, they turned to Roebling as the most experienced builder of cable suspension bridges in North America and asked him to put in a revised tender.

At first however it was not clear what would come of these plans. The bridge building committee, which comprised of the American Rochester Railroad and the Canadian Great Western, was often riven by internal disagreements and was at first happy to stick with the existing temporary Ellet bridge which sufficed for pedestrians and road traffic. This bridge was to serve until the opening of the road traffic deck of Roebling's bridge in 1854 (Edwards 1871).

Between 1848 and 1850 Roebling worked out several different draft versions for the company. At first Lot Clark, the director of the American Railroad Company, suggested the option of strengthening the existing bridge so that railway trains of a maximum weight of 200 tons could cross. In a letter of 13 October 1848 Roebling offered to build a 8.8 m wide one deck version for a

price of $128,000 and in the next few months created a draft for this solution **(Fig.7)**. The cross section was to have two pedestrian walkways each of 1.2 m, two carriage lanes each of 2.1 m and one 2.2 m wide railway line. The span was to be 244 m. The bridge was to hang on two 24.1 cm strong cables on four stone pillars, built with stylistic references to Egyptian columns. One reason for the reworked pillar draft might have been the parsimony of his clients, since the pillar version needed much less stone material. This is also suggested by the fact that Roebling's proposal was only possible as a minimal solution with considerable restrictions. Roebling's instructions would have meant that trains could only cross at reduced speed and would have prevented the simultaneous use of the bridge by trains and horses. In the same letter Roebling recommended his favoured alternative of a complete replacement of the bridge (AL B6 F42).

The British engineer Robert Stephenson, who had also been asked to work on a draft by the bridge building committee and who was investigating plans to build a bridge over the St Lawrence river near Montreal, proposed a tubular girder bridge with two piers and two abutments. The costs for the system he developed were much higher than for Roebling's light suspension construction. Stephenson's judgement of Roebling's draft was, "If your bridge succeeds, then mine have been magnificent blunders" (Berton 1992).

FINAL PLANNING AND IMPLEMENTATION

After a variety of investigation into differing plans and the presentation of their costs, Roebling finally managed to convince the bridge building company in favour of his original draft of a lattice truss box. Around two years passed between the end of Ellet's contract and Roebling receiving his contract in 1850 and a further two years passed until his final plan was accepted by the bridge committee. However, the company insisted that Roebling reused the wires of the bearing cable from Ellet's temporary bridge in his construction.

Roebling used the cable supporting Egyptian lone standing pillars from his earlier draft and added a covered arched passage to seal the lower deck. He did not insist on the use of wooden beams in the construction of the lattice truss as he had done in his first box draft, but rather used iron bands in their place, which made the construction even lighter and made the bridge appear lighter from the side. The anchoring of the span cable in the cliff was achieved not with four times five anchor chains, as originally had been planned, but with only four times two.

In his Report to the Directors of the Niagara Falls International and Suspension Bridge Companies from 28 July 1852 (AL B6 F44), he went into the technical details of the implementation of the accepted draft.

In the introduction he deals with the practicability of suspension bridges with large spans. Roebling judges Stephenson's critique of the system as simply a means of distracting attention for his own tubular girder system.

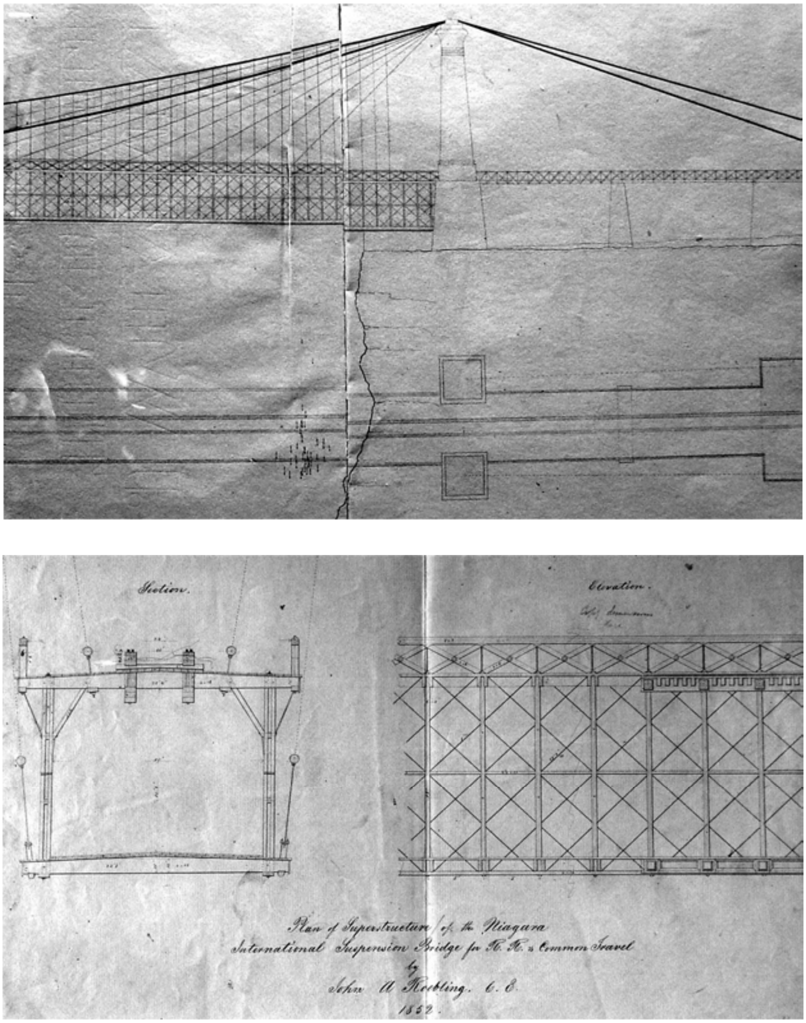


Figure 8. The implemented plan 1852 (TR OZ D4 F7)

Roebling argues that the bearing capacity of a suspension bridge depends essentially on the factors of the resistance of the materials and the rigidity of the construction. The tensile strength of tightened wire, which he gives as about 700 to 1,000 N/mm2 (collapse load), is superior to all other known building materials. In order to achieve a sufficient system resistance for the bridge, as well as the rigidity of the cables from wrapping, Roebling outlines the following three models:

1. The use of horizontal beams stiffened in mass and bending bearing capacity.
2. The use of trusses.
3. The stiffening of the system with stays.

To take the enormous load of the railway 1.2 m wooden beams were arranged under the rails, which at the same time also ensured the best possible distribution of the load effects in the bearing system at any given time. These beams sufficed as a complete bearing system for smaller railway bridges without needing any further measures, but with a span of 244 m additional stiffening was necessary. The choice of 5.5 m high and 6.1 m wide double-decker bridge helped the arrangement of two trusses in the side wall, which were connected by diagonal links as wooden boxes. Alongside the vertical stiffening from the trusses, an additional lateral rigidity is achieved for the whole system, which is further increased by the prestressing in the vertical beams created by the diagonal iron bands. Roebling mentions that another advantage of the diagonal iron bands is that it avoids wooden joints which are comparatively movable and reduce the resistance of the system. A horizontal giving way (buckling) of the truss level is not possible since at the final point the vertical poles take only pulling tension. The light open truss construction does not provide a lot of surface for the wind to attack. The stays over the top deck and under the lower deck give the system additional rigidity.

The rolling bearing on the pillars balance the tension in the bearing cables in case of an asymmetrical load. Each of the 18.3 m high pillars transfers the tension into the cliff earth with a maximum load of traffic from 4,910 ton and a total bridge load of 1,273 tons. The four cables with a diameter of 24.1 cm have a deflection of 16.5 m (upper level) and 18.0 m (lower level) and consist of a total of 13,560 wires. The maximum tension was mathematically hedged by a factor of five.

In conclusion Roebling once more discusses the single deck bridge draft which had already been dropped and mentions that it would have been more expensive than the double floor bridge because the necessary total of 12 m extra width would have required massive supporting columns with three times as much masonry instead of slim pillars.

THE CONSTRUCTION OF THE IRON SUSPENSION BRIDGE

During construction Roebling used Ellet’s temporary bridge as a working platform. After he gradually developed the cables of the existing bridge to work individual wires into the final construction, he checked the current pulling tension of the wires in order to be sure that they had not lost bearing capacity through the years of static and dynamic loads, but could not find any evidence of deterioration.

In 1852 work started on fitting of the eye-bars and cast iron plates as a grouted anchoring of the four bearing cables. The bearing cables each were assembled from seven separate strands connected by iron shoes and anchor chains. Every strand was made with 520 parallel individual wires and were temporarily covered with thinner wire at regular intervals to keep them in position after being made and were lifted to their final positions on the pillars using hoists. After all seven strands were ready the whole cable cross section was pressed together with clamps in order to cover the whole length of the cable with glued wire after careful oiling. Only around the saddles and adjacent to the

shoes was the cable not covered. The individual strands were made with a deflection of only about a third of the deformation that could occur with maximum demand in order to keep a certain cable tension and to ensure the activation of all the individual wires.

The bridge’s hollow box was attached to the four bearing cables with 624 suspenders. Additional horizontal rigidity was provided by the 64 rope stays attached to the upper deck and led over the roller saddles and 56 wire rope land stays as an anchoring of the lower floor. As he did in all his suspension bridges, Roebling arranged the levels of vertical suspenders at a slight angle. In the middle of the bridge the distance between the upper pairs of cables was 4.0 m, and 7.6 for the lower level cables. On the saddle the cables lay 11.3 and 11.9 m apart respectively (Edwards 1871). Roebling hung the bridge box with a camber of 1.5 m.

The traffic floor was opened to public traffic in 1854. On 18 March 1855 railway trains followed. At first many load tests were carried out. With a 34 ton train travelling at 12 km per hour and a full carriage on the bridge a maximum bending of 14 cm was measured. With a 326 ton train almost as long as the bridge there was an elastic distortion of 25 cm in the centre of the bridge.

Roebling himself believed that the construction of rigid railway bridges made of wood and iron hanging on bearing cables were very economical and predicted possible spans of bridges made only of iron of 600 m and more. Using steel rope he believed that spans of up to 1,600 m were feasible.

Roebling gave a figure of around $400,000 for the final cost of building the bridge, $220,000 more than in his original tender of 1847 (Roebling 1856).

THE PERIOD AFTER CONSTRUCTION UNTIL DEMOLITION

On 1 August 1860 Roebling published a report to the bridge building company on the bearing capacity of the Niagara bridge after five year of intensive use. The reason for this report was the demand to increase the permitted speed of trains from five miles an hour. Roebling offered a constructive strengthening of the bridge for $20,000. Because of the high amount of traffic of up to 45 trains per day, Roebling recommended replacing the rails on the bridge. After a comprehensive survey of the bending caused by the load of traffic no substantial change could be found from the results of 1855.

Roebling did observe a reduced stability in the Egyptian pillars and explained this disintegration with the extreme climatic conditions in the area. By recording the dynamic effects he established that the swinging of the superstructure was transferred to the bearing cables but not to the anchoring cables via the bedding saddles, which he saw as a very good means of anchoring.

However, in this position he failed to see that the stress would be transferred to the pillars if the roller bearing failed, which over time was to lead to weakening of the inelastic stone structure.

He was able to give an excellent bill of health to all the cables and all other iron materials such as the anchor chains and predicted that the bridge would last several hundred years if it were properly maintained (AL B6 F53).

The time of usage Roebling forecasted for his bridge shouldn't become true. After he died by accident in 1869 the Niagara Bridge until his demolition in 1897 several times needed maintenance mainly caused by the constantly growing amount of railway traffic and more and more massive locomotives.

In a text written in 1876 John Roebling's son Washington, himself a successful bridge engineer, replied to criticism of the Niagara suspension bridge from Edward Wasell and spoke about the then condition of the bridge.

The test load carried out when the bridge was opened in 1855 involved a load of 326 tonnes spread along the length of the bridge. In 1877 Washington Roebling was unable to establish an increase in the total load. However locomotives had become notably heavier, now weighing 45 tons instead of the 25 tons foreseen in the bridge draft of 1852. This increased concentration of weight was carried by the cable cross section without problem, but did lead to troubles with the stiffening elements of the construction. Washington Roebling noticed a mistake in the construction in the insufficiently sized upper and lower chords as a compression and tensile bars of the trusses of both side walls of the bridge. For this reason the vertical posts and the diagonal ties could not activate their bearing potential.

Washington Roebling praised his father's plan for the slim pillars, which passed the resulting load directly to the foot of the pillars in the middle of the cross section. This meant that the size of the pillars could be reduced by about a third. He also paid tribute to the high placement of the pairs of bearing cables since this achieved an optimal position for the centre of gravity of the middle of the cross section, which also contributed to an improved distortion rigidity of the superstructure (BR TG 25 N57).

After investigations into the state of the bridge since 1873, in 1877 a comprehensive analysis of its condition was undertaken by Thomas C. Clark, W. H. Paine and C. McDonald (AL Bound Items Washington Roebling ENG #6). The following conclusions were reached.

The bearing cross section in the bearing cables was reduced by the influence of the weather in the root point anchoring. Individual wires and their covering were replaced. Since the anchoring had suffered rust damage, an extra anchor chain was added to each root point to strengthen them **(Fig.10)**.

The investigation also showed that the wooden superstructure had marked signs of attrition. The knot ties had become looser with time and constant variation in stress, which led to measurable

bending twice as high as had been observed when the bridge was new. For this reason the wooden truss work was replaced by an iron construction of the same type **(Fig.10)**.

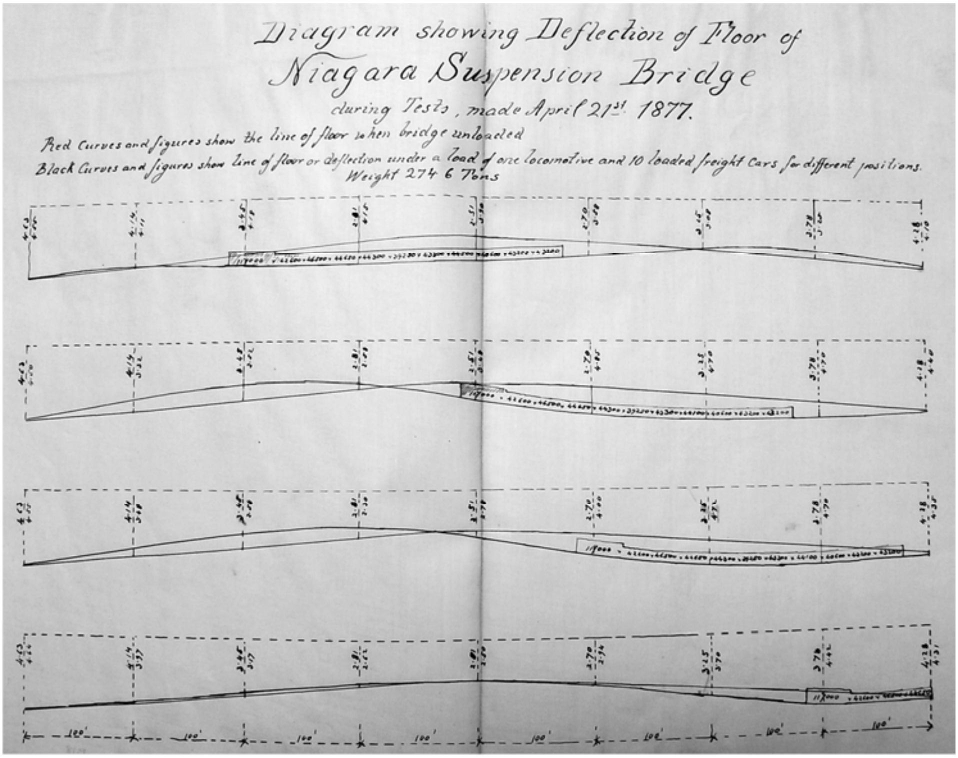


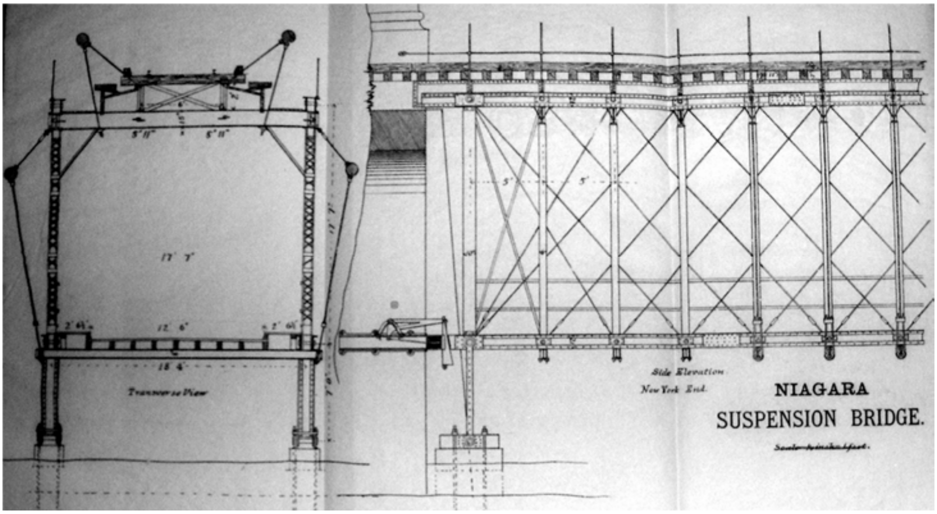
Figure 9. Bridge testing 1877 by Clark, Paine and Mc Donald, diagram showing deflection of floor under train load, (AL Bound Items Washington Roebling ENG #6)

Leffert L. Buck, an experience bridge engineer who had studied with Washington Roebling, was given the task of doing the necessary alterations to the bridge. In 1880 after finishing his work, Buck published his report (Buck 1880).

Because of the extreme weather conditions combined with the dynamic action, signs of deterioration could be observed in the masonry. The roller bearings had lost their sliding effect due to rust and dirt, which meant that the static and dynamic tension was transferred straight to the pillars. After replacing individual bricks over and over again, it was decided in 1886 to replace the pillars altogether because of the general bad state they were in (Buck 1899).

In order not to interrupt traffic, the four corners of a pillar were removed and iron profiles put in their place. Gradually the stone pillars were replaced by iron towers. After finishing this work all that remained of the original bridge were the cables, saddles, suspenders and anchorages. It had

been planned to use parts from the original bridge in the construction of another bridge, but this never happened because of cost considerations.



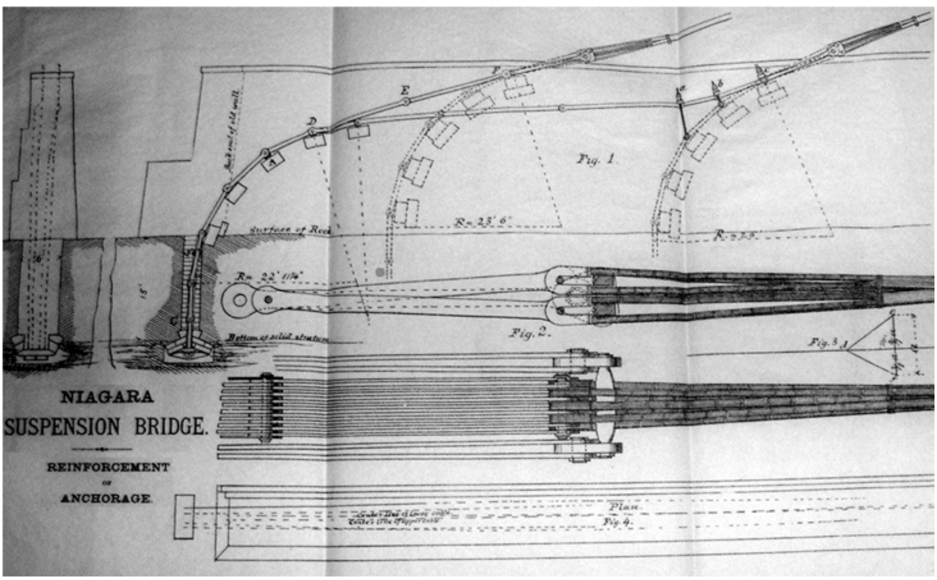


Figure 10. Restoration in 1880 by Leffert L. Buck, showing the new trusswork and the additional anchorage (TR TG 25 N57)

Because of costs and the need for a modern and maintainable bridge, sixteen years later the repaired bridge was entirely replaced by a two hinged steel arch bridge also designed by Leffert L. Buck.

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